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STUDY OF SOME OPTIONS FOR THE CLIC FINAL FOCUSING QUADRUPOLE

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Abstract

This paper describes a feasibility study and the preliminary design for the CLIC final focusing quadrupoles. A possible design for a quadrupole consisting of rare-earth permanent magnet material is introduced. Due to its radiation hardness and its high remanence, Sm_2Co_{17} seems to be the best suited permanent magnet material. The very high field gradients of 450 T/m can be achieved if pre-magnetized sectors made of permanent magnet material are assembled in ”zero clearance” design. An alternative solution with small superconducting coils is presented and briefly discussed, but would need further investigations.

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Study of some Options for the CLIC Final Focusing Quadrupole

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Summary

This paper describes a feasibility study and the preliminary design for the CLIC final focusing quadrupoles. A possible design for a quadrupole consisting of rare-earth permanent magnet material is introduced. Due to its radiation hardness and its high remanence, Sm_2Co_{17} seems to be the best suited permanent magnet material. The very high field gradients of 450 T/m can be achieved if pre-magnetized sectors made of permanent magnet material are assembled in "zero clearance" design. An alternative solution with small superconducting coils is presented and briefly discussed, but would need further investigations.

1 Introduction

The Compact Linear Collider (CLIC) study at CERN proposes an e^+e^- collider that combines a 3 TeV center-of-mass energy , high-gradient acceleration of 150 MV/m and a high luminosity of $10^{35}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ [1]. The required spot sizes in the interaction point are $\sigma_x^* = 43\,\mathrm{nm}$ in the horizontal and $\sigma_x^* = 1\,\mathrm{nm}$ in the vertical plane. This is below the smallest single beam size of 70 nm so far observed. The optical design of a CLIC beam delivery section has been described for a standard [2] and a short [3] version. Imperfections occur along the whole linac and beam delivery sections (alignment offsets, vibrations,. . .) leading to an emittance growth or generating trajectory errors mainly due to transverse quadrupole offsets. Hence the design luminosity will be reduced significantly if the imperfections cannot be kept at a minimum level. This translates into a requirement on the stability of the magnetic center in the quadrupoles of better than 4.0 nm rms (horizontal) and 0.2 nm rms (vertical) uncorrelated motion above 15 Hz. To achieve this very ambitious goal of mechanical stability a vibration test-stand has been set-up at CERN [4].

2 CLIC Requirements for the Final Focus System

Table 1 summarizes the geometrical and magnetic requirements as well as environmental conditions for the two versions of the final focusing system (see [2] and [3]). The physical dimensions in a plane perpendicular to the beam axis are further restricted by the beam pipe that has to be fitted into the bore of the magnet. For the calculations presented in this paper, the beam pipe has been assumed to have a thickness of $t_\mathrm{p} = 0.2\,\mathrm{mm}$. Hence the inner bore of final focusing magnet system has to be $\geq r_\mathrm{a} + t_\mathrm{p}$. Further design work has to be done to determine the exact dimensions of the beam pipe, and moreover to design the vacuum

	standard version	short version
Quadrupole field	450 T/m	388 T/m
Quadrupole length	4.75 m	3.50 m
Sextupole field	—	100 kT/m^2
Aperture r_a	3.3 mm	3.8 mm
Outer radius r_o	20 mm	43 mm
Distance to interaction point	2.0 m	4.3 m
External magnetic field	4–6 T	0 T
Field stability	$< 10^{-5}$	$< 10^{-5}$
Vertical stability of magnetic center	≤ 0.2 nm	≤ 0.2 nm

Table 1: *Geometrical and magnetic requirements for the two versions of the final focusing system.*

system. The magnet system has to be designed in a way that space can be allocated to the vacuum system in periodic locations along the beam axis.

In addition the outer radius r_o determines the maximum outer dimensions of the whole magnet system including the support structure.

The expected power deposit in the magnet is 0.5–0.8 W from photons, electrons and coherent pairs (electrons lose energy by bremsstrahlung, radiation length of, e.g., $\mathrm{Sm_2Co_{17}}$ $X_0^{\mathrm{Sm_2Co_{17}}} \approx 1.58\,\mathrm{cm}$). This energy deposit would be equivalent to a dose of $\approx 10\,\mathrm{krad/h} = 100\,\mathrm{Gy/h}$ if the radiation was equally distributed along the magnet. In reality the radiation will increase when approaching the interaction point.

3 Permanent Magnet Material or Superconductors?

3.1 Coil Dominated Superconducting Magnet System

In this section we present a preliminary design of a superconducting final focusing quadrupole. Figure 1 shows a possible cross section of such a magnet. The following items have to be considered for a coil dominated superconducting final focusing magnet:

- Due to the very small dimensions, small conductors have to be used. The conductors shown in Fig. 1 are keystoned, 0.4 mm wide on their smaller side, 0.7 mm wide on their bigger side and 5 mm high (0.05 mm of insulation). The cable contains six superconducting strands with a diameter of 0.6 mm. In each strand a copper to superconductor ratio of 1.6 has been assumed. These parameters are meant to represent a reasonable first guess for a preliminary design but will have to be reconsidered during a more detailed design including the quench protection issues.

- Due to the very limited space, it will be difficult to design the constant perimeter coil ends with very small bending radius. This item needs further investigations.

- The electromagnetic forces acting on the conductors will be up to 8500 N/m. Hence strong collars have to counteract these forces and hold the cables in place.

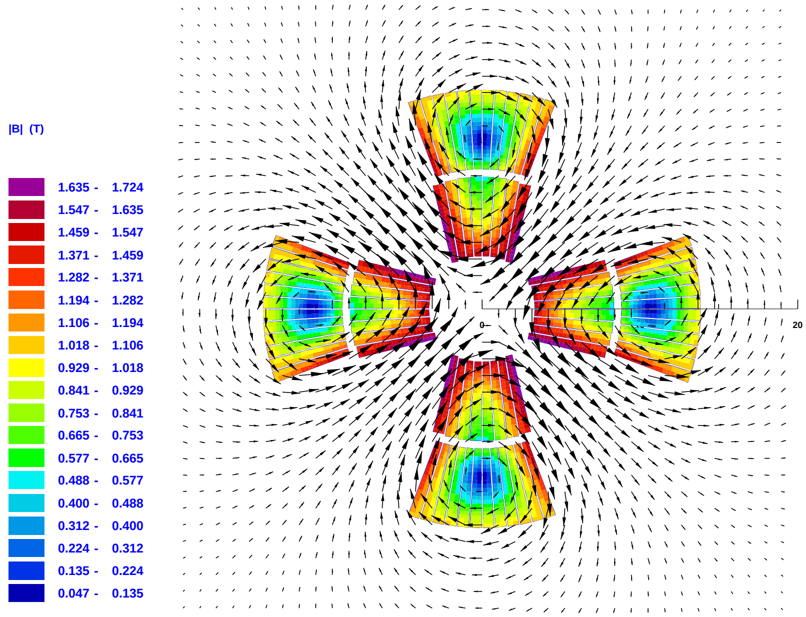

Figure 1: *Coil dominated quadrupole, $G \approx 460\,\mathrm{T/m}$ at $I = 1750\,\mathrm{A}$. ROXIE computation [5].*

- Cooling with liquid He at 1.9 K is preferable [6], for liquid He at 4.5 K additional space for the vapor phase would be necessary.
- The cryostat needs at least 6–10 mm space around the coils [6]. In the cross section shown in Fig. 1 a space of 6 mm for the cryostat around the coils has been taken into account. In principle one could imagine a slightly conic cryostat with a growing cross section with increasing distance from the interaction point.
- For a heat load of 10 W (0.5–0.8 W beam loss + isolation losses) a liquid helium cross section (at 1.9 K) of $\approx 6.5\,\mathrm{cm}^2$ is needed [6]. This would require large cooling slots inside the collars ("swiss-cheese" like collars).
- The cross section of the connections to the cryostat has been estimated to be $2 \times 6.5\,\mathrm{cm}^2$ [6].
- For NbTi at 1.9 K and the above mentioned cable parameters (current of $I = 1750\,\mathrm{A}$) the percentage on the load line calculates to $\approx 53\,\%$. Including an external longitudinal field of 4 T the percentage on the load line rises to $\approx 80\,\%$. Depending on the nature and the distribution of the energy deposit in the superconductor the resulting quench margin of 20 % could be sufficient for a safe operation. This corresponds to a temperature margin of about 1 K. However, this has to be further investigated including simulations of the energy deposit in the superconducting cables.
- The vacuum pumps needed for the system can be located in a certain distance, but considering the stringent stability requirements the vibrations of these pumps could cause problems.

To summarize, such a superconducting magnet solution would certainly not be easy to realize. Some important points (e.g. coil ends, quench margin, pump vibrations, ...) have to be investigated in greater detail.

3.2 A Permanent Magnet Solution

In view of the stringent stability requirements for the CLIC final focusing quadrupoles and the very small dimensions of the magnet cross sections (see Table 1), a permanent magnet solution without the need for a cryogenic system seems to be favorable. This section presents the calculations performed for a permanent magnet final focusing system.

3.2.1 The Choice of the Material

Highest gradients are achievable with rare-earth permanent magnet material in "zero clearance" assembly. In this kind of design some pre-magnetized sectors are assembled in ring form. The sectors are magnetized in such a way that the magnetization direction approximates the direction of the field lines. This design has already been proposed for focusing quadrupole magnets by K. Halbach [7]. The greater the number of sectors, the higher becomes the achievable field gradient.

Different rare-earth permanent magnet materials were taken into consideration: $SmCo_5$, Sm_2Co_{17}, and $Nd_2Fe_{14}B$. Table 2 shows typical values for some of the properties of these materials. The exact properties depend on the production process[1] and are listed in, e.g., [8]. The maximum field without demagnetizing the permanent magnet material H_{cJ} also depends

Material	B_r (T)	H_{cB} $\left(\frac{kA}{m}\right)$	Temp. Coeff. of B_r $\left(\frac{\%}{°C}\right)$	Therm. Exp. Coeff. $\left(\frac{10^{-6}}{K}\right) \perp \vec{B}$	Density $\left(\frac{g}{cm^3}\right)$	Spec. Heat $\left(\frac{J}{kg \cdot K}\right)$
$SmCo_5$	1.0	700	-0.04	13	8.4	370
Sm_2Co_{17}	1.1	800	-0.03	12	8.4	390
$Nd_2Fe_{14}B$	1.3	1000	-0.10	-1	7.6	440

Table 2: *Comparison of three rare-earth permanent magnet materials. The table shows typical values, the exact values depend on the production process [8] (B_r is the remanence, H_{cB} is the coercitivity).*

strongly on the production process, but for all three materials the highest possible values are around[2] $H_{cJ} \approx 2000\,\mathrm{kA/m}$, (i.e. $\approx 2.5\,\mathrm{T}$). Hence for the standard version (see Section 2), where the final focusing quadrupoles will extend into the solenoidal detector field, a screening of the magnetic field will be necessary. This can be done by building an "anti"-solenoid around the final focusing quadrupole.

Although the coercitivity and remanence of $Nd_2Fe_{14}B$ is higher than for the Sm compounds, the magnetic properties depend much stronger on the temperature (see Table 2).

[1] Especially the press-direction has a big impact on the magnetic properties.

[2] Some companies offer specially optimized magnets that go up to higher values, e.g., VACODYM 411 ($Nd_2Fe_{14}B$): $H_{cJ} = 3200\,\mathrm{kA/m}$.

All rare-earth permanent magnet materials are anisotropic and brittle. Due to the anisotropy, the sectors of permanent-magnet material will have to be pre-magnetized and afterwards assembled to a permanent ring magnet.

The permanent-magnet material is produced in pieces of approximately 7–8 cm length, hence the several meter long magnet will be held together by the enveloping stainless steel tube. In between the pieces, space for the vacuum system can be provided if necessary.

Another important aspect is the radiation hardness:

- Measurements with a 17 MeV electron beam [9]: At a dose of 1.7 MGy the measured magnetic flux loss was $\leq 0.4\,\%$ for Sm_2Co_{17}, and $\leq 8\,\%$ for $Nd_2Fe_{14}B$. According to [9], the radiation effect on the magnetic flux comes from the local heating effect along particle tracks.

- Measurements with ^{60}Co γ rays [9]: At a dose of 2.8 MGy the magnetic flux loss was $\leq 0.5\,\%$ for Sm_2Co_{17} and $Nd_2Fe_{14}B$ (maximum energy of secondary electron is 0.8 MeV).

- No damaging effect has been observed for neutrons ($E > 0.5\,\mathrm{eV}$) up to an integrated flux of 10^{18} neutrons/cm^2 for Sm_2Co_{17}.

- In the CLIC final focusing system the expected dose is between 100 and 5000 Gy/h. This will lead to a slow magnetic flux loss.

These measurements suggest, that Sm_2Co_{17} is maybe the most suitable material for the final focusing system due to its high radiation hardness and hence long term stability, provided the required field gradients can be achieved.

The company Vacuumschmelze in Hanau, Germany gave a price estimate of ≈ 1000 DM/kg ≈ 510 Euro/kg for VACOMAX 225 (Sm_2Co_{17}). It has to be assured, that a radiation-hard glue is used to assemble the pre-magnetized permanent magnet sectors.

3.2.2 A Permanent Magnet Ring Quadrupole for the Standard Beam Delivery Version

Figure 2 shows the cross section of the final focusing quadrupole in the standard beam delivery version. The dimensions are given in Table 1. The thickness of the beam pipe was assumed to be 0.2 mm. The stainless steel tube around was assumed to have a thickness of 1 mm. The 16 sectors are magnetized in the following way: Be n an index counting the sectors in mathematically positive sense, starting at $n = 0$ for the sector with the symmetry axis lying on the positive x-axis. Then the n^{th} sector has to be pre-magnetized in an angle $\psi_n = 90\,^\circ + n \cdot 45\,^\circ$ with respect to its symmetry axis.

Such a permanent magnet ring quadrupole has a gradient of $G \approx 468$ T/m for the permanent magnet material VACOMAX 225 HR (Sm_2Co_{17}) that has a coercitivity H_{cB} of 820 kA/m, and a remanence B_{r} of 1.1 T [8]. This is enough for the CLIC final focusing quadrupole.

Using the dimensions from Table 1 leads to a weight of ≈ 10 kg/m magnet length, the enveloping steel tube excluded.

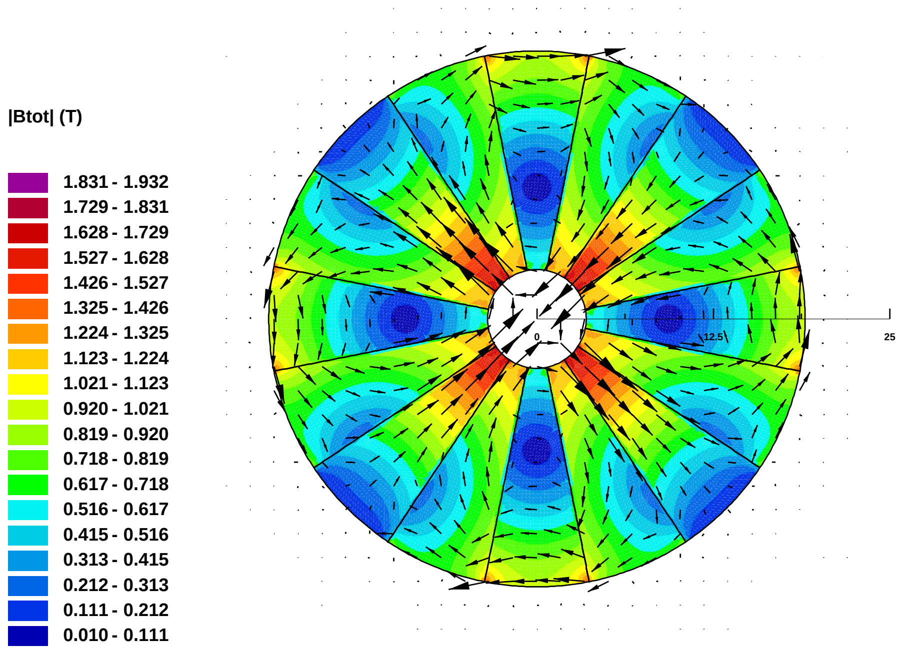

Figure 2: *Cross section of a permanent magnet ring quadrupole in "zero-clearance" design made of 16 pre-magnetized sectors.* $G \approx 468\,\mathrm{T/m}$ *for the permanent magnet material VACOMAX 225 HR* (Sm_2Co_{17}). *ROXIE computation [5].*

3.2.3 A Permanent Magnet Ring Sextupole for the Short Beam Delivery Version

For the short beam delivery version the final focusing quadrupole has a larger aperture but also a considerably lower required field gradient. ROXIE [5] computations showed that a field gradient of $G = 390\,\mathrm{T/m}$ can easily be achieved with a similar design (and adapted dimensions) as shown in Fig. 2. Using the dimensions from Table 1 leads to a weight of $\approx 50\,\mathrm{kg/m}$ magnet length, the enveloping steel tube excluded.

In addition to the final focusing quadrupole the short beam delivery version requires a very strong sextupole magnet. Figure 3 shows the cross section of a permanent-magnet sextupole (permanent magnet material VACOMAX 225 HR [8]). The sextupole field is $\approx 91\,\mathrm{kT/m^2}$, which is 10 % below the required value (see Table 1). It seems possible to compensate the lower field by increasing the length, but the impact on the beam dynamics has to be investigated. Another solution would be to use $Nd_2Fe_{14}B$ as permanent magnet material that shows higher values for the coercitivity and remanence (see Table 2). This seems to be a viable solution, since the radiation at the position of the sextupoles is significantly lower than at the quadrupole positions (larger distance from the interaction point) and hence radiation hardness might be a minor issue. However, this has to be verified by simulating the radiation environment using dedicated software. The 24 sectors are magnetized in the following way: Be n an index counting the sectors in mathematically positive sense, starting at $n = 0$ for the sector with the symmetry axis lying on the positive x-axis.

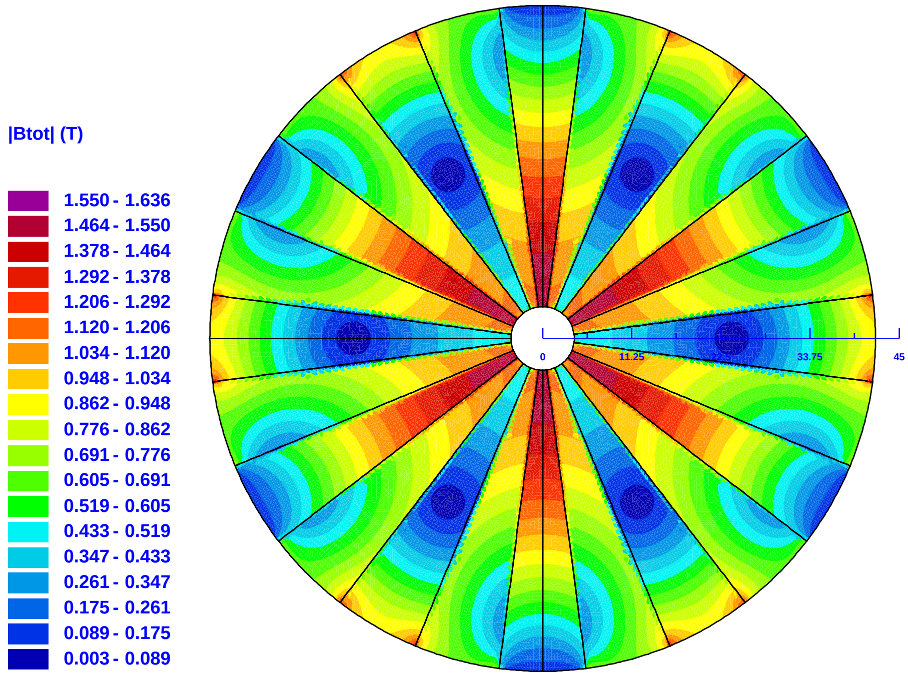

Figure 3: *Cross section of a permanent magnet ring sextupole in "zero-clearance" design made of 24 pre-magnetized sectors. The sextupole field is* $\approx 91\,\mathrm{kT/m^2}$ *for the permanent magnet material VACOMAX 225 HR* ($\mathrm{Sm_2Co_{17}}$)*. ROXIE computation [5].*

Then the n^{th} sector has to be pre-magnetized in an angle $\psi_n = 90^\circ + n \cdot 45^\circ$ with respect to its symmetry axis.

3.2.4 Forces during the Quadrupole Assembly

To estimate the forces that appear during the permanent-magnet assembly, one sector was pulled out of its original position and a magnetic force computation was performed. The magnetic force was calculated using ROXIE (for a more detailed description of the force calculations see [10]). Figure 4 shows the cross section of the quadrupole (permanent magnet material VACOMAX 225 HR [8]) with one sector shifted for 10 mm out of its original position.

Figure 5 shows the force, that is – due to symmetry – parallel to the radial direction ($\vec{F} \parallel \vec{e}_r$). For a small shift out of the original position, the force is negative, i.e. attracting, for a bigger shift, the force is repulsive and reaches its maximum of 900 N/m at a shift of ≈ 12 mm. Beyond this maximum, the force decreases quickly. For small shift distances the attracting force becomes very large.

These results were obtained by calculating the force contribution of the integral of the Maxwell stress tensor along the line from the starting point $(0.71, 0.71)$ to the end point $(125.43, 84.04)$ (all coordinates in mm). Parts of this line are illustrated by the solid line in Fig. 4.

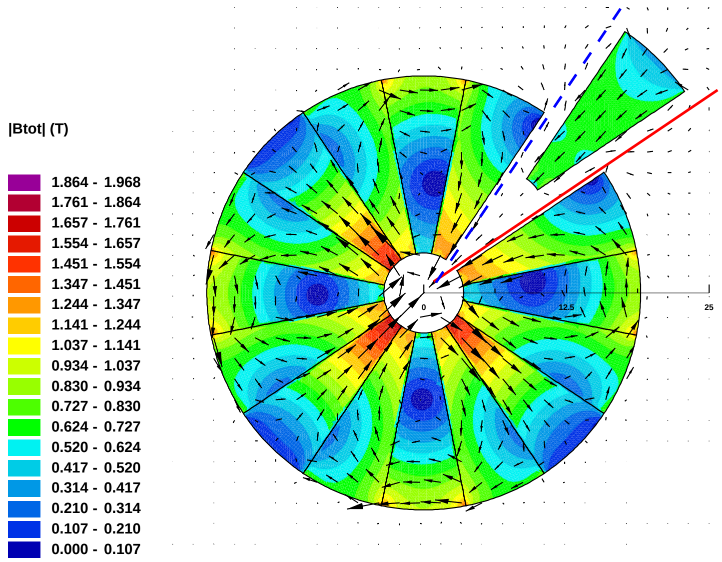

Figure 4: *Cross section of a permanent magnet ring quadrupole in "zero-clearance" design. One sector is shifted for* 10 mm *out of its original position.*

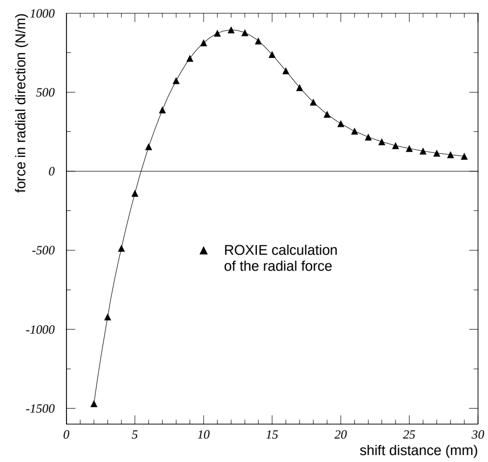

Figure 5: *Variation of the force ($\vec{F} \parallel \vec{e}_r$) as a function of the radial shift of one sector out of its original position.*

3.2.5 Shift of the Magnetic Center due to Temperature Differences

In order to obtain an estimate for the temperature dependence of the position of the magnetic center, a field computation has been performed taking into account the temperature dependence of the remanence B_{r} (value see Table 2). For simplicity reasons, a model of the quadrupoles of each beam delivery version with only 8 sectors has been used. The field gradient of such a design is significantly lower then for the proposed solution with 16 pre-magnetized sectors. Nevertheless, the result should give us a feeling of the expected effect. One half of such a magnet was then "heated up by 1 °C", i.e., the magnetic properties in one half have been modified during the computation. The mechanical expansion due to temperature has not been taken into account[3].

Table 3 summarizes the results of the computation. Note, that the gradients for both beam delivery versions are not sufficient due to the simpler design with only 8 pre-magnetized sectors instead of 16. For the mechanical dimensions of both versions see Table 1. The equivalent asymmetric energy deposit denotes the energy that is needed per unit length to heat up one half of the quadrupoles for 1 °C. The difference between the two designs is due to their differences in size. The rather unrealistic assumption of a homogeneous heating has been used. The shift of the magnetic center Δd goes into the direction of the warmer half. The last line of Table 3 denotes the maximum allowed difference in energy deposit per unit length in the two permanent magnet halves when restraining the shift of the magnetic center

[3]The final design of the permanent-magnet quadrupoles has to consider enough space (slackness) between the pieces along the beam-axis direction in order to avoid deformations (bendings) due to temperature expansion

to 0.2 nm.

	standard version	short version
Field gradients	389 T/m	377 T/m
Temp. diff.	+1 °C	+1 °C
Equiv. asymm. energy deposit	1800 J/m	9000 J/m
Shift of magn. center Δd	199 nm	286 nm
Max. energy deposit diff. for $\Delta d < 0.2$ nm	1.8 J/m	6.3 J/m

Table 3: *Shift of the magnetic center due to asymmetric temperature distibutions in the final focusing quadrupoles (see text for more explanation). ROXIE computation [5] for the permanent magnet material VACOMAX 225 HR* (Sm_2Co_{17})*.*

4 Conclusion

This note describes a preliminary design for the CLIC final focusing quadrupoles. A solution using pre-magnetized sectors made of rare-earth permanent magnet material assembled in "zero clearance" design seems most favourable, although further design work (mechanical stability, support structure, ...) is necessary. Another quadrupole solution using superconducting coils to produce the high field gradients seems more difficult to implement, but might be a viable fall-back solution.

The required high field gradient of 450 T/m for the standard beam-delivery version can be achieved using the rare-earth permanent magnet material Sm_2Co_{17}. This material is favourable to other materials due to its radiation hardness and its weaker temperature dependence. However, the standard beam-delivery version requires an active shielding of the detector field (using, e.g., an "anti"-solenoid coil), whereas in the short version the quadrupoles do not extend into the detector field region. The very strong sextupole fields necessary for the short version can also be produced using rare earth permanent magnet material.

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